LCA Case Studies

LCA of Multicrystalline Silicon Photovoltaic Systems

Part 2: Application on an Island Economy

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Part 1: Present Situation and Future Perspectives • Part 2: Application on an Island Economy

Preamble. This series of two papers which is based on a Diploma Thesis (N. Stylos, 2000) presents the LCA performed for a Multicrystalline Photovoltaic (PV) system and a full scale application on an island. **Part 1** (Koroneos, Stylos and Moussiopoulos 2006) presents an energy analysis for all the PV components, extended to the primary energy carriers. In **Part 2**, a complete and accurate identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed, for an installation of a multicrystalline photovoltaic park on a Greek island.

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Abstract

Aim, Scope and Background. The environmental and energy parameters of Photovoltaic systems play a very important role when compared to conventional power systems. In the present paper, a typical PV-system is analyzed to its elements and an assessment of the material and energy requirements during the production procedures is attempted. An LCA is being performed on the system of production of photovoltaics.

Main Features. A complete and accurate identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed. The emissions analysis is extended to the production of the primary energy carriers. This allows having a complete picture of the life cycle of all the PV-components described in the present study.

Methods and Tools. In order to obtain concrete results from this study, the specific working tool used is the Eco-Indicator '95 as being reliable and has been widely applied within LCA community A process that relates inventory information with relevant concerns about natural resource usage and potential effects of environmental loadings is attempted.

Conlusions. The analysis of all previous impact categories has shown that large-scale PV-systems have many advantages in comparison with a conventional power system (e.g. diesel power station) in electricity production. As a matter of fact, PV-systems become part of the environment and the ecosystems from the moment of their installation. Burdens are released from the PV-systems only during their manufacturing procedures.

Recommendation. Technological improvements need to be done in the manufacture of BOS-components which consume during their life cycle almost equal amounts of energy as the photovoltaic modules.

Keywords: Eco-indicators; energy pay-backtime (EPE); mc-silicon solar cells; multicrystalline silicon photovoltaic systems; PV-systems; silicon; solar cells; threshold limit values

Introduction

The investigation of the environmental effects, caused during the different life cycle stages of a product, constitutes a great part of a LCA study. Thus, it is crucial to examine the following environmental effects:

1. CO_2 equivalent emissions and the greenhouse effect
2. CFC-11 equivalent emissions and the ozone depletion effect
3. SO_2 equivalent emissions and the winter smog effect
4. C_2H_4 equivalent emissions and the summer smog effect
5. SO_x (or SO_2) equivalent emissions and the acidification effect
6. Phosphate equivalent emissions and the eutrophication effect
7. Heavy metals
8. PAH equivalent emissions and Carcinogenesis
9. H_2SO_4 equivalent emissions (air, water, soil, underground, transfer) and ecotoxicity
10. Radioactive emissions

1 Environmental Impacts

In each category of effects, diagrams showing the equivalent emissions of the chemical compounds, which contribute to these effects are presented. The emissions, which result from the production procedure and the transport of the raw materials of the PV-components (Swiss Agency for the Environment, Forests and Landscape (SAEFL 1998), are compared to the emissions resulting from the operation of the conventional diesel power unit which supplies, for the time being, island Nisyros with electricity (Data taken from Hellenic Public Power Company). In order to convert the different chemical emissions to equivalent emissions, the Eco-Indicators and Threshold Limit Values (TLV) are used. These values are 'Immediately dangerous to Life and Health' (IDLH 2000). **Table 1** is a memorandum of the symbols and the operational period of time (O.P.T) of the power systems for the technical cases considered (Koroneos et al. 2003).

Table 1: List of abbreviations

Memorandum		
Case	**Symbol**	**O.P.T.**
Base-alum.0%:	BC.0%	30 yr
Base-alum.50%:	BC.50%	30 yr
Improved-alum.0%	IC.0%	40 yr
Improved-alum.50%	IC.50%	40 yr
Forward-alum.0%	FC.0%	50 yr
Forward-alum.50%	FC.50%	50 yr
KC60-alum.0%	KC60.0%	30 yr
KC60-alum.50%	KC60.50%	30 yr
Diesel	Diesel	30,40,50 yr

1.1 CO_2 equivalent emissions and the greenhouse effect

A basic measure of the environmental profile of a product is the amount of CO_2 that is released during its life cycle stages. **Fig. 1** presents the overall CO_2 equivalent emissions in gr/O.P.T., the CO_2 equivalent emissions in gr/kWh electricity produced and the CO_2 equivalent emissions in gr/kWh of final energy source consumed, for the two different power systems. (Eco-Indicator 1995, RIVM, NL Environmental Ministry & Green Design Initiative, Carnegie Mellon).

The differences between all the PV-cases and the diesel power station case are huge in all CO_2 diagrams. Differences of 2 orders of magnitude are noticed, which could substantially become greater if the construction of the diesel power station was taken into account. The 50% aluminum recycle has a benefit but it cannot affect dramatically the whole PV-system. Perhaps, in case of a wider usage of recycling materials in all PV-components the benefits would be greater.

1.2 Ozone depletion

The CFC-11 equivalent emissions are at a very high level in the diesel power station case in comparison with those of PV-cases, which are extremely low. The usage of recycled aluminum seems to be of marginal benefit.

However, clear conclusions can not be drawn from the CFC-11 emissions in gr/kWh of final energy sources consumed-values, because in some cases the released emissions are greater when 50% recycled aluminum is used. This means that for the present technological status and for the use of the specific energy sources, the recycle procedures of aluminum release more CFC-11 emissions/kWh of energy sources consumed than producing and using 0% recycled aluminum. All the previous can be seen in **Fig. 2**.

1.3 Winter smog

For evaluating winter smog, the Winter Smog Potentials (WSP) are used for converting the different chemical emissions (dust, SO_2) to an equivalent basis. The equivalent emissions of SO_2 are negligible in PV-cases in comparison with the diesel case, as shown in **Fig. 3**. Specifically, the differences between them are at least of 1 order of magnitude. The contribution of recycled aluminium seems to have negative effects to the ecosystem.

On the other hand, the comparison between any of the PV-cases and the diesel power station case presents a ratio of SO_2 equivalent emissions in gr/kWh of electricity produced equal to 1/10 which confirms the environmental profile of photovoltaic systems.

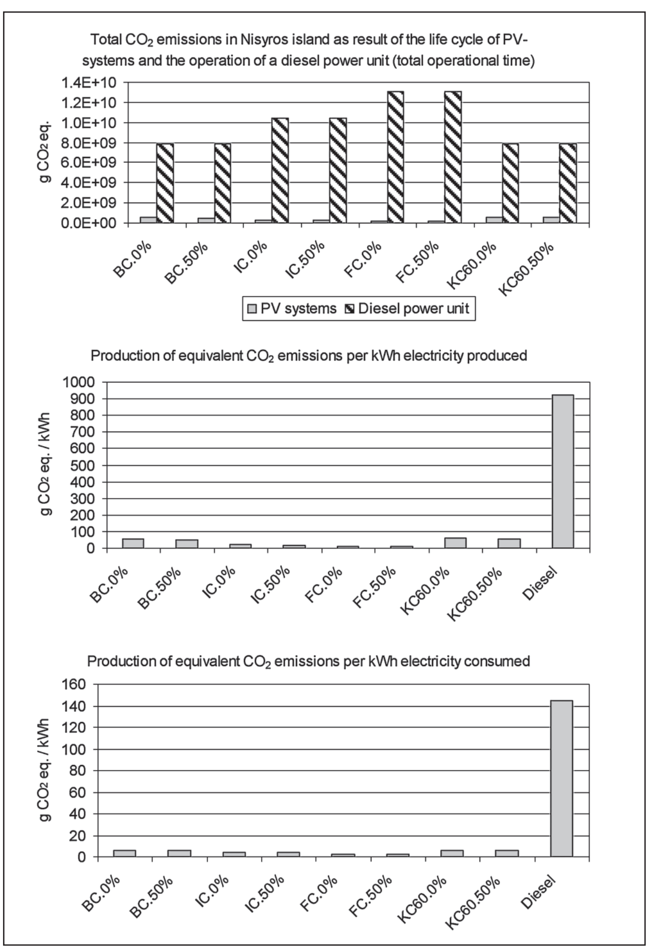

Fig. 1: Diagrams of the equivalent emissions of CO_2 over PV-systems' lifetime and during the operational period of time of diesel power station

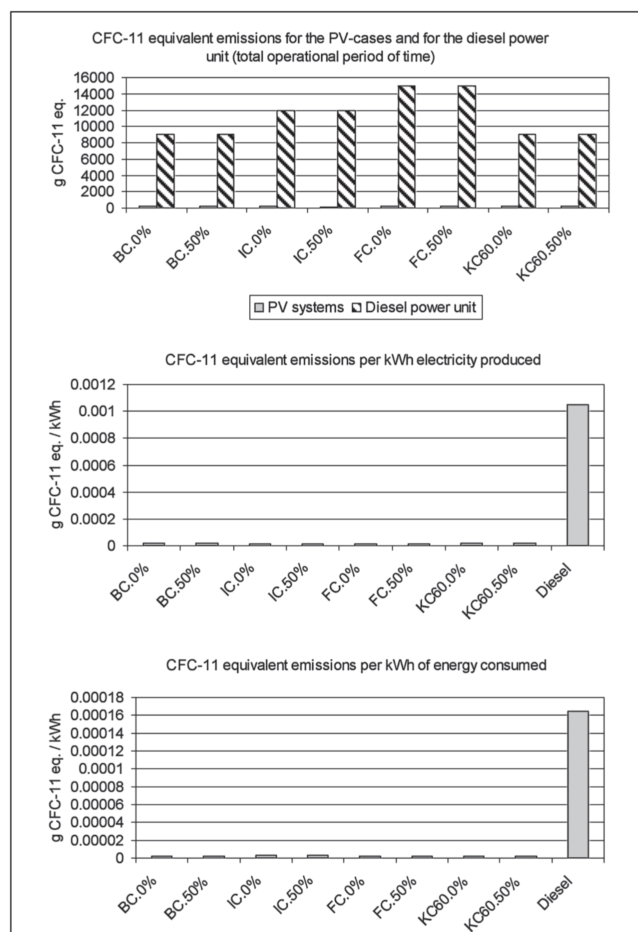

Fig. 2: Diagrams showing the equivalent emissions of CFC-11 over PV-systems' lifetime and during the operational period of time of diesel power station, which contribute to ozone depletion

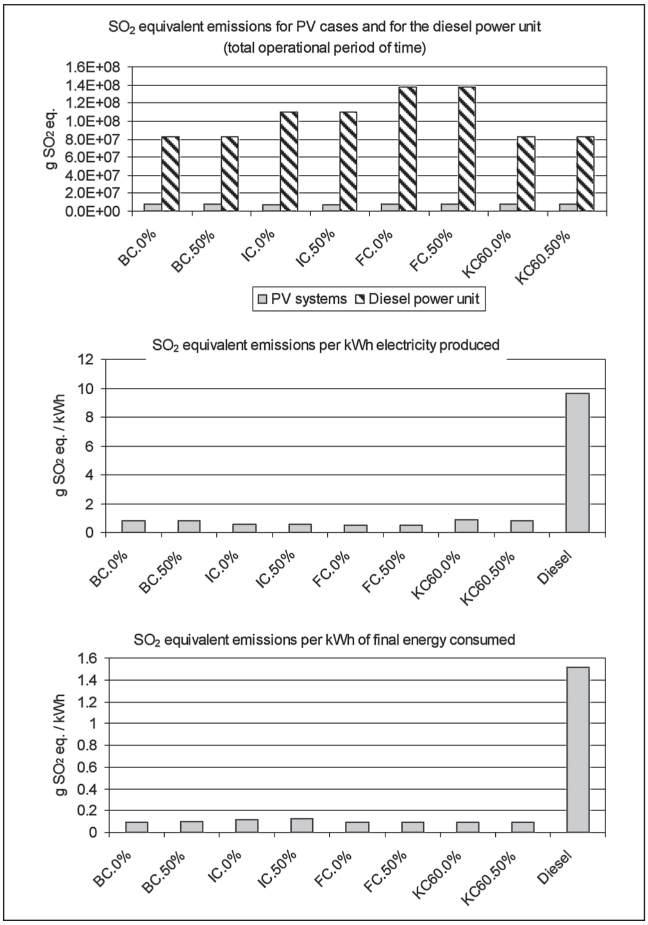

Fig. 3: Diagrams showing the equivalent emissions of SO_2 over PV-systems' lifetime and during the operational period of time of diesel power station, which contribute to winter smog

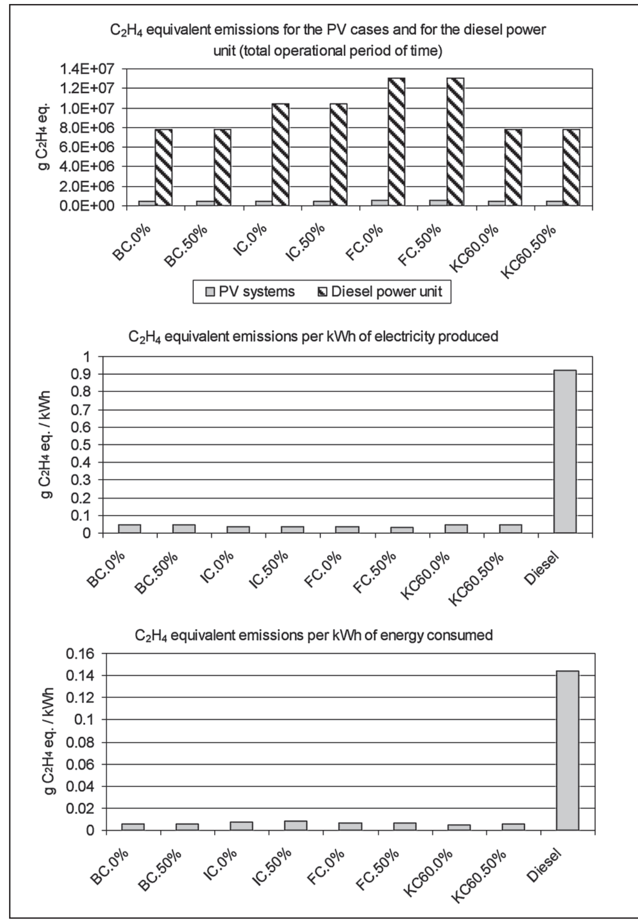

Fig. 4: Equivalent C_2H_4 emissions, over PV-systems' lifetime and during the operational period of time (O.P.T) of diesel power station, which contribute to the summer smog effect

1.4 Summer smog

For the smog effect, which takes place in the summer season, all the different chemical emissions (e.g. propene, chlorophenols, hydrocarbons etc.) which affect the atmosphere as smog, are converted to C_2H_4 equivalent emissions. **Fig. 4** presents the main diagrams for this impact category. The same conclusions can be drawn for the C_2H_4 equivalent emissions as for SO_2 emissions of the winter smog effect without any significant differences.

1.5 Acidification

Acidification is measured as the amount of protons released into atmosphere. The weighting factors are presented either as mol of H^+ or as kg of SO_x equivalent. SO_2 and SO_x emissions are considered to have the same effect on this impact category. **Fig. 5** presents the main diagrams for this impact category. Chemicals like ammonia, HF, HCl and NO_x contribute to this impact category.

All PV-cases have an advantage in this category, over diesel case. The released equivalent SO_x emissions in gr/kWh of electricity produced are 10–12 times greater in diesel case than in every PV-case. The main characteristic is that for SO_x emissions/kWh of consumed energy sources, the highest emissions are observed in improved aluminum 50% case.

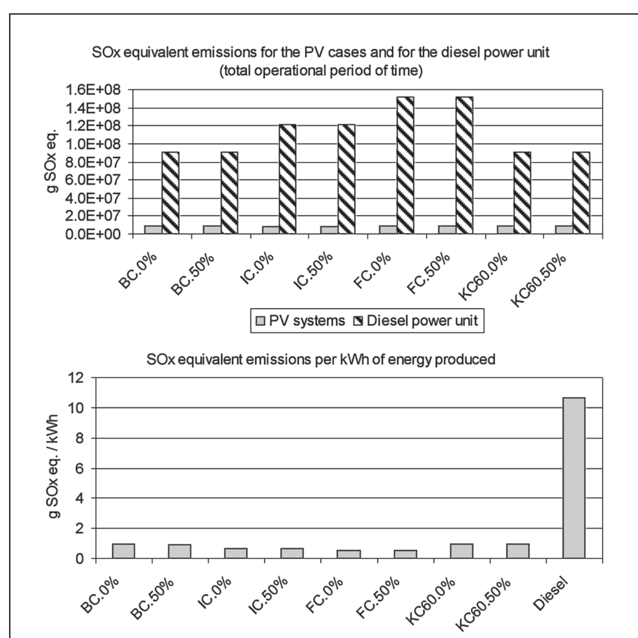

Fig. 5: Equivalent SO_x emissions, over PV-systems' lifetime and during the operational period of time (O.P.T) of diesel power station, which contribute to the acidification effect

This means that the combination of energy sources on the previous case produces the greatest amounts of SO_x emissions per kWh of consumed energy resources. As a consequence, it can be concluded that the production of 1 kWh of electricity from the PV-installation of improved case-alum. 50% (using fewer PV-modules than in base cases) has as a serious drawback, the increased release of emissions.

1.6 Phosphate equivalent emissions and the eutrophication effect

Nitrogen and phosphorus are essential nutrients for the regulation of ecosystems. Enrichment (or eutrophication) of water and soil with these nutrients may cause an undesirable shift in the composition of species within the ecosystems. Eutrophication of terrestrial ecosystems is mainly due to (long distance transport of) atmospheric emissions of NO_x (nature areas) and emissions to soil of nitrogen and phosphorus (agricultural areas). Eutrophication of coastal waters and of larger inland waters can be largely attributed to (long distance transport of) emissions from household, industry and surface run-off from paved or from agriculture. High concentrations in surface water and groundwater (by leakage) can make these waters not drinkable.

Nutriphication potentials are available for all important eutrophying compounds. There are available nutriphication potentials for compounds in air and water and for this reason, the emissions which are released in air are studied separately from those released in water.

The same results appear in the eutrophication category where the equivalent emissions of phosphate (PO_4^{3-}) in air and water are calculated separately (**Fig. 6** and **7**).

It is worth mentioning that in all PV-recycled aluminum cases, the phosphate emissions are slightly increased in comparison with the normal PV-cases, due to recycle procedures.

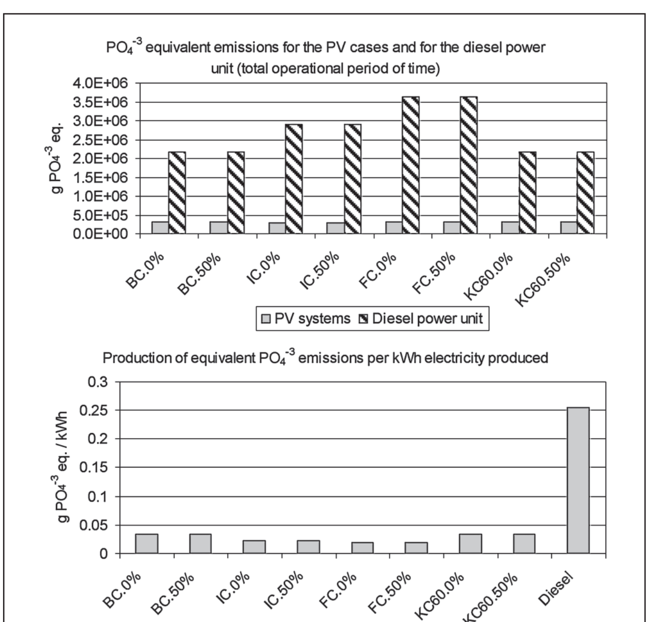

Fig. 6: Diagrams showing the equivalent air emissions of phosphate, over PV-systems' lifetime and during the operation of Diesel unit

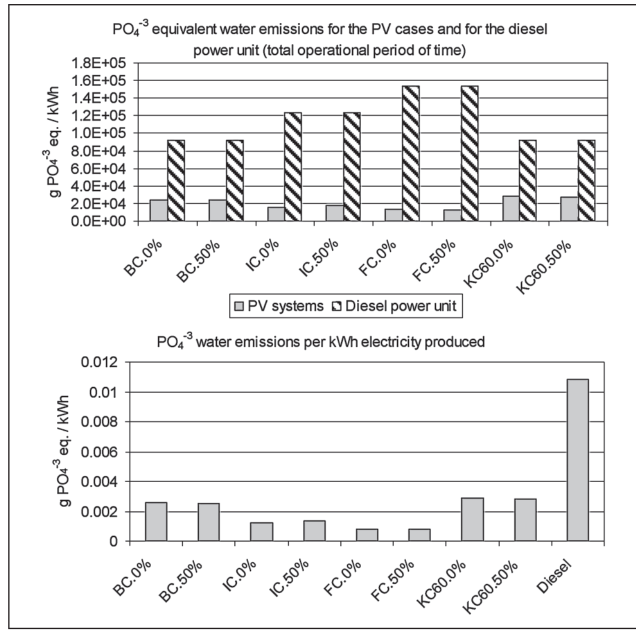

Fig. 7: Diagrams showing the equivalent water emissions of phosphate over PV-systems' lifetime and during the operational period of time of diesel power unit, which contribute to Nutriphication

1.7 Heavy metals

This category refers to the releases of heavy metals to the environment, air and water. For evaluating the total contribution, the emissions of all the chemical compounds of this category (e.g. Cd, Hg, Mn, Pb, As, Cr, Sb, Cu) are converted into equivalent emissions of lead (Pb). **Fig. 8** and **9** summarize the results of the calculations.

The heavy metals emissions are calculated in equivalent emissions of lead (Pb) in air and water. It can be seen that in

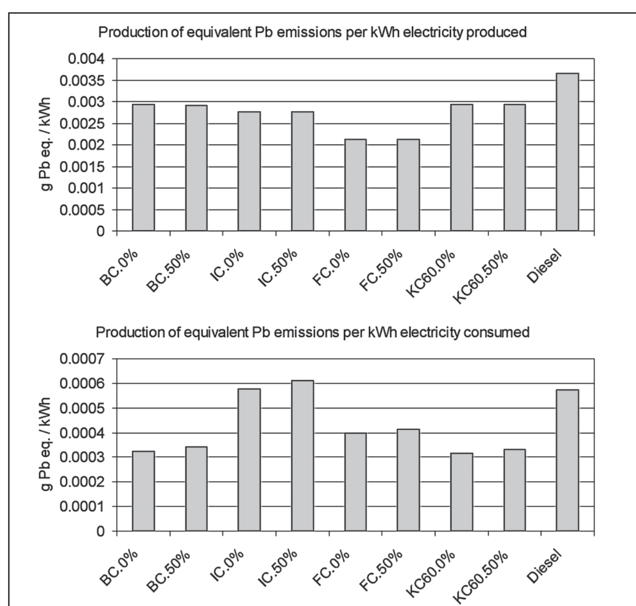

Fig. 8: Diagrams showing the equivalent air emissions of Lead (Pb), over PV-systems' lifetime and during the operational period of time of diesel power station. (heavy metals)

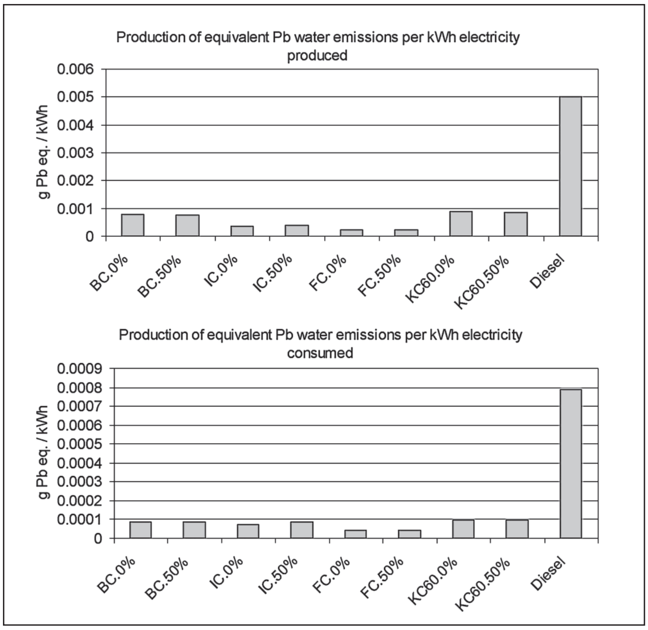

Fig. 9: Diagrams showing the equivalent water emissions of Lead (Pb), over PV-systems' lifetime and during the operational period of time of diesel power station

air the lead emission levels in PV-cases are about the same with those released during the operation of diesel power station. On the other hand, in water there is an appreciable difference between the two technologies. This impact category requires extra attention because the releases of heavy metals can cause serious damages to the ecosystem.

1.8 PAH equivalent emissions and carcinogenesis

Chemical compounds like Chrome, Benzene, Nikel, Polycyclic Aromatic Hydrocarbons (PAH) and other, are considered to be responsible for Carcinogenesis. Thus, all the emissions which are relevant to this impact hace been calculated on an equivalent basis.

In the category of gases, which are responsible for carcinogenesis, it can be seen that PV-systems have a great advantage due to the fact that PAH (Polycyclic Aromatic Hydrocarbons) equivalent emissions are negligible. The PAH equivalent air emissions are in every PV-case close to zero, which means that large-scale usage of PV-technology will not cause direct health problems to the people living close to PV-industries. **Fig. 10** presents the equivalent air emissions for PAH.

1.9 H_2SO_4 equivalent emissions (air, water, soil, underground, transfer) and ecotoxicity

Toxicity of the ecosystems is perhaps the most serious problem of the modern high technology. In many cases, the need for best performance of the products forces the industries to use chemicals which are toxic. After the production procedures, the wastes have a high level of toxicity. For this reason it is always useful to study and calculate the toxic emissions which are released during the production or/and the operation, usage of a product.

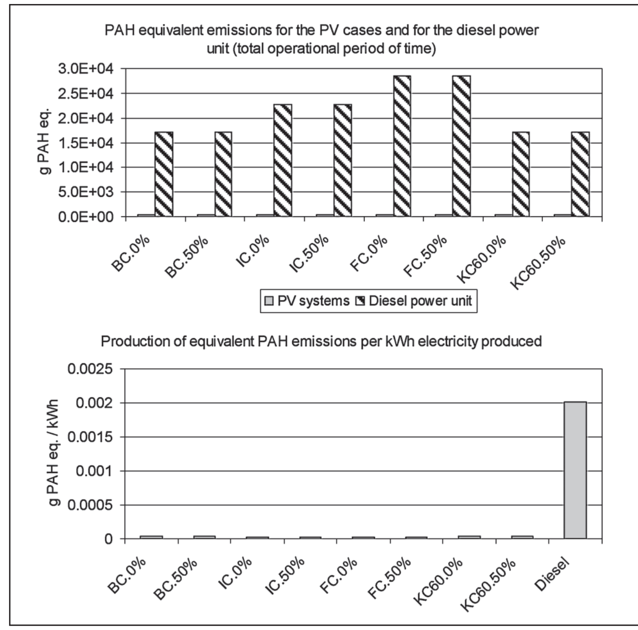

Fig. 10: Diagrams showing the equivalent air emissions of PAH (Polycyclic Aromatic Hydrocarbons), over PV systems' lifetime and during the operational period of time of diesel power station, which are responsible for Carcinogenesis

All different toxic emissions are converted to H_2SO_4 equivalent emissions. **Fig. 11** presents the equivalent H_2SO_4 emissions for the PV-system.

The H_2SO_4, in this category, represents all the toxic chemical substances.

Based on Fig. 11, it is obvious that the production and operation of PV-systems burdens more the environment with toxical substances compared to the operation of a diesel power station.

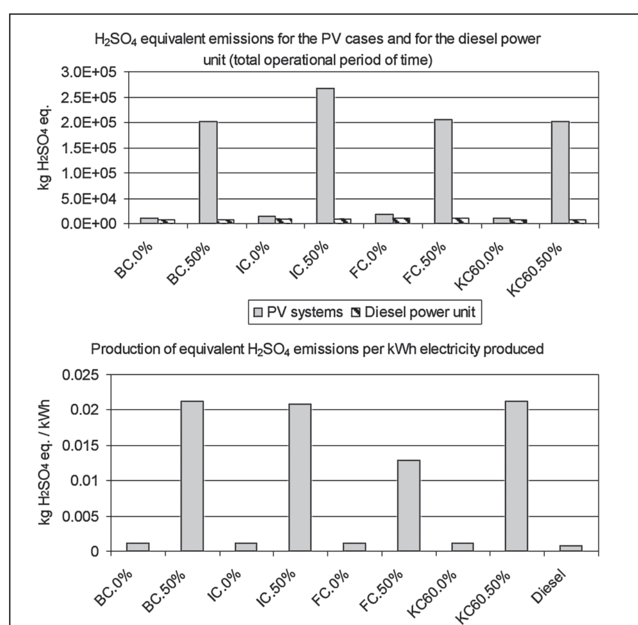

Fig. 11: Diagrams showing the equivalent emissions of H_2SO_4, over PV-systems' lifetime and during the operational period of time of diesel power station, which are responsible for ecotoxicity

It is worth mentioning that this study does not refer to the whole life cycle of the diesel power unit, but only to its operation. If a full LCA of the diesel power unit was implemented then the results would be even more in favor of the photovoltaic systems.

Finally, it is important to notice that toxic substances in all PV-systems are released mainly from batteries and inverters.

1.10 Radioactive emissions

Radioactive emissions and wastes are certainly 'scarce' in modern technology. They are measured in Bequerel (Bq) and the consequences of their release in the ecosystems are of long duration. **Fig. 12** and **13** show the relevant diagrams for radiactive emissions in air and water respectively.

From Fig. 12 and 13, it can be seen that radioactives exist in higher emission levels in various PV-cases in comparison with the diesel case, both in air and water.

Although there are different 'ups and downs', it seems that in future the PV-systems production will release fewer amounts of radioactive compounds.

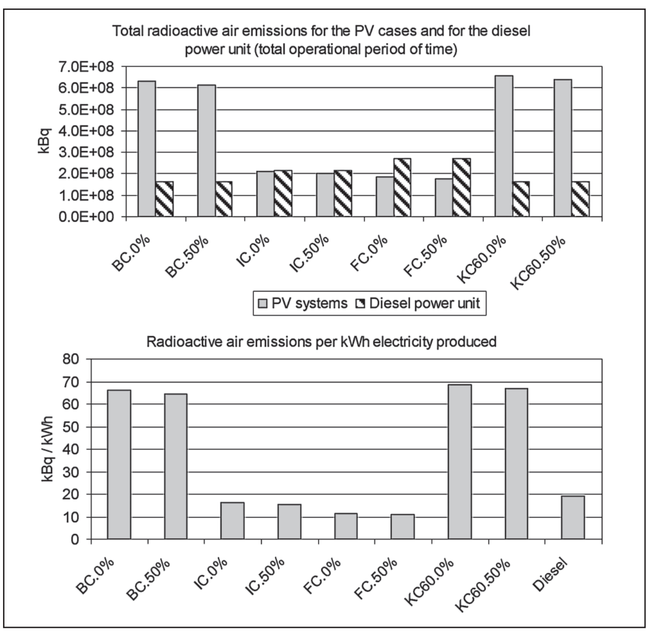

Fig. 12: Diagrams showing the equivalent radioactive air emissions, over PV-systems' lifetime and during the operational period of time of diesel power station

2 Conclusions

In general, the analysis of all previous impact categories has shown that large-scale PV-systems have many advantages in comparison with a conventional power system (e.g. diesel power station) in electricity production.

The air emissions, which are responsible for various atmospheric effects, are minimized with the usage of PV-systems. As a matter of fact, PV-systems become part of the environment and the ecosystems from the moment of their installation. Burdens are released from the PV-systems only during their manufacturing procedures.

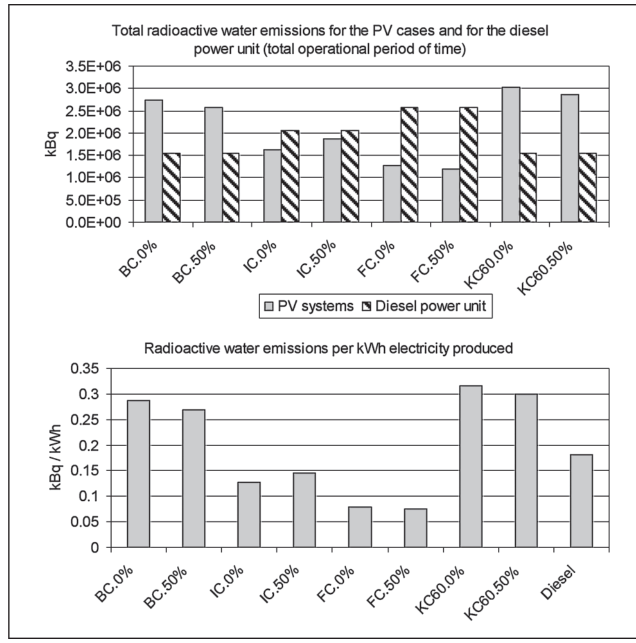

Fig. 13: Diagrams showing the equivalent radioactive water emissions, over PV-systems' lifetime and during the operational period of time of diesel power station

On the other hand, they are responsible for high toxic and radioactive emissions in comparison with the correspondent diesel power station. This is true for the present PV-technology but the predictions for the future PV-technology improvements are very encouraging, as it results from the relevant diagrams.

It is also important to note that the resources assumed for the production of PV-systems are conventional. If PV-systems is considered as a technology for large-scale 'world' energy supply (e.g. 5 or 10% of world electricity supply), then it could be assumed that the electricity requirements for manufacturing PV-systems can be covered from the electricity produced by PV-systems. This would make PV-technology a totally 'clean' solution for electricity production.

References

Eco-Indicator (1995): RIVM, NL Environmental Ministry & Green Design Initiative, Carnegie Mellon Green Design Initiative, Economic Input-Output Life Cycle Assessment, Carnegie Mellon University (1999) <http://www.eiolca.net>

Koroneos C, Stylos N, Moussiopoulos N (2003): LCA of multicrystalline silicon PV Systems. Laboratory of Heat Transfer & Environmental Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

Koroneos C, Stylos N, Moussiopoulos N (2006): LCA of Multicrystalline Silicon Photovoltaic Systems. Part 1: Present Situation and Future Perspectives. Int J LCA 11 (2) 129–136

Swiss Agency for the Environment, Forests and Landscape (SAEFL) (1998): Life cycle inventories for Packagings (Vol. I, II), Berne

Threshold Limit Values (TLV) (2000): Values Immediately dangerous to Life and Health (IDLH) <http://www.airgas.com/products/productdata/threshold.html#note>

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